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SOIL PROPERTY IMPROVEMENT USING SLAG BINDER

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ABSTRACT

In the majority of cases this is cement, which is used for soil improvement both for sandy soils and clays in order to increase its strength and reduce its compressibility. However this effect could be reached by using lime or in some cases slag binder for soil improvement. Comparing with cement and lime blast furnace slag used for improvement of soft clays prove more effective.

Soils can be improved by means of wet soil mixing or dry soil mixing. The result is that we get a new composite material and its strength is much higher when comparing with natural soils. This technology can be used easily provided that physical mechanism that affects soil behavior of composite material is defined. Mechanical properties of composite material can be defined through its testing using simple as well as complex stress paths, whose are necessary in cases where more complex functional relationships are used.

Test results show that soil strength and stiffness properties are highly dependent on the content of slag. Increase in the total water to total solids ratio causes decrease in the mixture strength. Increase in the curing time produced increase in the mixture strength.

OBJECTIVE OF THIS PAPER

In most cases this is cement, which is used to reinforce both sandy soils and clays in order to reduce its strength and to improve its deformation behavior /16, 14, 11/. However, it is common knowledge, that such soil behavior can be reached through soil reinforcement by means of lime /4/, or, in some cases, by means of slag binder /15, 7/. The usage of blast-furnace slag appears more effective for reinforcement of soft soils compared to cement and lime /7/.

This class of soft soils includes ooze, peat and high- and fluid-plastic loamy soils. Modulus of elasticity for such soils is usually less than 5 MPa, which is why such soils show high compressibility. Natural foundation settlement on such soil is large, for that reason it is not recommended as a foundation. Usually such soils are replaced with more solid soils or modified i.e. reinforced soils.

Physical and mechanical properties of natural soft soil can be evaluated by means of currently used methods such as GOST 12248-96 /5/. Then the calculation of foundation settlement can be made by means of the formula given in SP 50-101-2004 /13/:

$$s = \beta \sum_{i=1}^{n} \frac{(\sigma_{zp,i} - \sigma_{z\gamma,i}) h_i}{E_i} + \beta \sum_{i=1}^{n} \frac{\sigma_{z\gamma,i} h_i}{E_{e,i}} \qquad (1)$$

Where: β – non-dimensional coefficient, which is equal to 0,8; E_i – stress-strain modulus of i-soil layer according to the primary loading path; $E_{e,i}$ – stress-strain modulus of i-soil layer according to the secondary loading path; $\sigma_{zp,i}$ – the average value of vertical normal stress due to external load applied to the i-soil layer; $\sigma_{zy,i}$ – the average value of vertical normal stress accrued in the i-soil layer due to excavated soil dead weight. Provided that the depth of excavation is less than 5 m, the second element of the formula (1) is not used while calculating the settlement.

According to the formula (1), the settlement can be reduced by increasing of stress-strain modulus for natural soil, i.e. by reducing its compressibility through reinforcement by one or another method. In this case the grade of reinforcement is known preliminary, as it is fixed in SP 50-101-2004 and according to the type of construction ranges from 12 to 40 cm. E.g. if the soil pressure equals to 200 kPa (constructions up to

10 floors), elasticity module according to norm should be not less than 30 MPa. In most cases, natural soil has an elasticity modulus, which is equal to 5 MPa. I such a case the strength of natural soil need not less than a 6-fold increase.

It is possible to reinforce natural soil through admixing of cement by one or another method /3, 12/. As a result we get a new composite material, which strength is much bigger than a natural one. Such technology can be easily applied, if the mechanical behavior of composite material is known. The mechanical properties of composite material can be obtained by means of both simple and complicated stress paths tests. The latter is necessary, if more complicated calculation methods comparing to the formula (1) are used.

In the overwhelming majority of researches made both in Russia and overseas this is cement, which is used for such tests. Slag binder is used very seldom. At the same time, tests carried out by Russian scientists /15, 7/ have shown essential advantages of using slag as a binder instead of cement.

In many cases the factors effecting the mechanical properties of soils reinforced by cement such as the amount of cement, curing time and mixing technology were estimated by means of unconfined compression test /14, 11, 1/. However, it is commonly known that stress-path behavior of soils reinforced by cement depends not only on the amount of cement used along with lateral pressure, but it is also highly influenced by the type of loading applied /17, 8/. As a result, tests should be carried out using devices, which allow simulating different stress-path conditions.

Because of the fact that the strength of soil-cement mixture or slag-soil mixture is an intermediate value, which ranges from the soil strength up to the strength of normal concrete, it is possible to apply standard methods used for testing concrete as well as for soils to estimate its mechanical properties.

Standard tests can be applied for estimating of material properties such as compression and tensile strength. It is known a lot of researches, where the results of dynamic and static unconfined compression test of concrete are presented. Additional data concerning plasticity and strength of concrete can be obtained through multiaxial loading of samples. The results of such tests show the full range of information, which can be used for modeling and verifying the models obtained.

However, there are other methods, which are used for advanced stress-path testing of soils, in particular, axisymmetric triaxial test. Summing up, this paper presents different methods applied for both concrete and soil testing.

METHODS USED FOR REINFORCEMENT OF NATURAL SOILS BY MEANS OF SLAG BINDER

The aim of our study to reinforce soft soils through adding slag binder can be reached by the following technical means:

1. It is necessary to reinforce soft soil by using in-depth mixing method (wet method) and adding developed composite slag material (slag-soil) so as it could provide the construction with the strength and strain needed.
2. It is necessary to calculate the strains affecting the soil as well as its bearing capacity in order to estimate the sufficiency of the strength and strain of the soil base designed according to SP 50-101-2004.
3. Bearing capacity and strain of the foundation should be calculated by means of methods given in SP 50-101-2004 only if the stress-strain curve of the foundation is linearly elastic or by means of computation if the stress-strain curve is non-linear /2, 9/.
4. For the selected methods it is necessary to test composite material in order to model induced elastic and inelastic material behaviour.
5. Using the method selected and the parameters obtained we should estimate the bearing capacity and strain of the improved soil.
6. Provided that the calculated values of bearing capacity as well as strength are not sufficient, it is necessary to change properties of composite material and repeat actions given in 1-5.

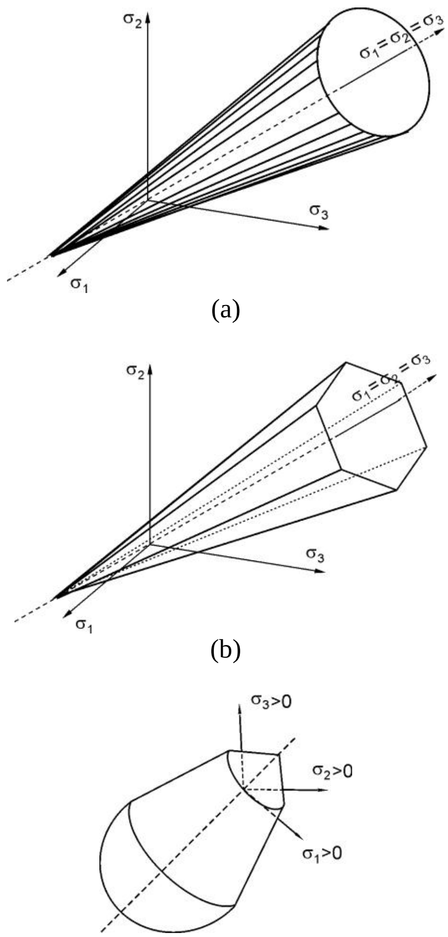
Both natural and reinforced soil can be estimated by means of different theories/models. In each of the theories given below the parameters used, were obtained through testing different kinds of materials. In the case under study these are natural soils and slag material used to improve natural mechanical properties of soils.

In order to estimate the bearing capacity and strains of the soil base needed according to /12, 13/ it is necessary to define mechanical properties of both natural and reinforced soil (Table 1).

Table 1. Mechanical properties of materials

Type of method	Density ρ, g/cm^3	Stress-strain modulus E_0, MPa	Young's modulus E, MPa	Poisson's ratio ν	Bulk modulus K, MPa	Shear modulus G, MPa	Angle of internal friction φ, deg.	Cohesive force c, kPa
Bearing capacity	+						+	+
Strain	+	+	+	+	+	+		

Fig. 1 presents properties, needed for calculation of bearing capacity and deformation of soil in case analytic methods given in /12, 13/ are used. These methods allow us to to model linear elastic material behavior of soil foundation provided that the grade of plastic deformation progress does not exceed one fourth of foundation width.



(c)

Fig. 1. Strength surface of Drucker-Prager (a), Mohr-Coulomb (b) and (c) Cap model.

Structural monitoring and practical experience in construction show, that natural soils and especially those reinforced by any binder can endure more loads and with larger grade of plastic deformation progress.

However, in this case it is not possible to apply methods given in /12, 13/ and we have to use nonlinear mechanic and numerical approach, in particular finite element analysis /2, 9/. Provided that finite element methods are applied for strength and strain calculation, some additional mechanical properties not included in table 1 should be provided. Type and quantity of such properties are defined according to the models used for materials and according to strength needed.

The most commonly used in actual practice are strength criteria of Mohr-Coulomb, Drucker-Prager, Cam-Clay, Cap /2,3,9/.

The simplest model describing the strength of material is strength criteria of Mohr-Coulomb, which consists of only two parameters: angle of internal friction φ and cohesive force c.

$$f(\sigma)=2c\ \cos\varphi - (\sigma_1+\sigma_3)\sin\varphi - (\sigma_1 - \sigma_3)=0. \qquad (1)$$

Mohr-Coulomb criterion allows existence of tensile behavior of material (Fig.1 a).

Summing up, while foundation designing it is necessary to select deformation theory/material model and afterwards define through testing parameters needed for the models selected. Some of the parameters are presented in the Table 1, type and quantities of others should be defined according to the model of concrete or soil selected. As mentioned above, soils are slightly affected by tensile stress. At the same time, being reinforced by the slag, such soils show certain tensile strength. Taking this, it seems necessary to evaluate not only compressibility of such a material, but also its tensile strength: for soils – only compressive stress, whereas for clay-slag materials – both compressive and tensile stresses. In order to calculate the foundation according to the tensile strength (e.g.by means of crack opening model) it is necessary to define additional parameters, which are called stress intensity factors /18/. These parameters are presented in Table 2.The Procedure for evaluation of the stress crack resistance is given in GOST 29167-91 /8/.

Table 2. Stress intensity factors

Soil behavior	Factors applied
Crack development under elastic and plastic behaviour of material	K – stress intensity factor; K_c – critical stress intensity factor under maximal loading; K_i – critical stress intensity factor under static loading; K_c^* – conditional critical stress intensity factor; K_{ij} – actual values of stress intensity factors due to incremental balanced loading; J – integral

Some other concrete testing parameters defined in GOST 10180-90 are not presented in the Tables 1, 2 /4/. These are: unconfined compression test, R; axial tensile strength, R_t; tensile splitting strength; bending strength, R_{tf} and prism strength R_{np}. Some of the parameters mentioned (R_{np}, R_t, R_{tt}) are used in practice to calculate the strength of concrete structural building components such as foundations, beams, columns etc. according to SNiP 2.03.01-84* /12/. These are prism strength R_{np} and axial tensile strength R_t.

EQUIPMENT FOR MATERIAL STRESS TESTING

For the models study a fully automated multifunctional testing system ASIS was fabricated and listed into State Register of approved measuring instruments of Russian Federation /10/.

Schematic diagram of testing system IVK ASIS is shown in Fig.2. The amount of the devices included to this testing system may vary. The choice (amount and type of devices) depends on the model and parameters selected.

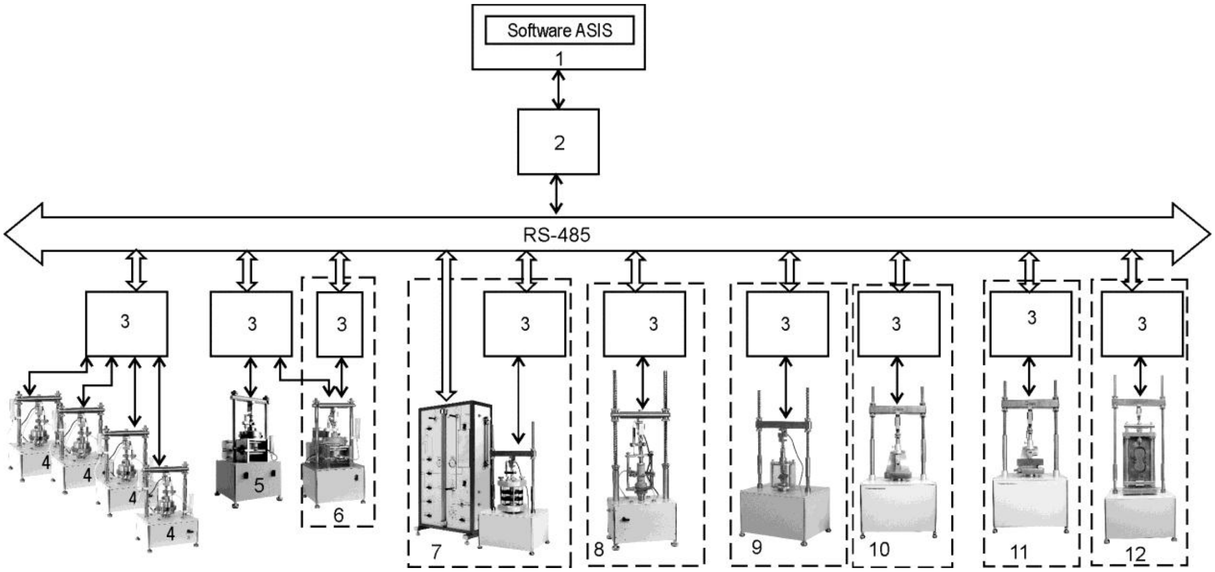


Fig. 2. Schematic diagram of testing system IVK ASIS:
1 – PC; 2 – interface converter; 3 – data acquisition unit; 4 – odometers; 5-6 – direct shear device; 7 – triaxial testing device; 8 –unconfined compression testing device; 9 –tensile strength testing device;10 – indirect tensile strength testing device; 11 – beam bending test device; 12 – direct tensile test device

This system allows conducting tests in fully automated mood with subsequent data processing. For this purpose special software programs were developed to control the tests procedure as well as for data storage and acquisition.

The software of IVK ASIS consists of system and application software. System software includes operating system (WINDOWS or others) and additional software which provides control and management of all measurements and equipment through interactive graphics mode as well as exchange of information within subsystems and testing technical condition of equipment. The software is a set of subroutines, which allow:

- efficient representation and data processing, experiment designing, testing workflow operation;
- testing data backup;
- calibration of IVK ASIS.

RESULTS

Specimens made from clay by adding NaOH as an activator and by using different proportions of slag were tested by means of IVK ASIS. The granulated slag manufactured according to GOST 3476-74 by Lipezky metal factory were used as a binder. The specific surface area of the powdered slag S = 300 – 350 m^2/kg. Tests were made by using specimens containing 10, 20 and 30 % of powered slag and 2 % of NaOH as an activator. While testing curing of specimens were made under pressure of 100, 200 and 300 kPa.

Tests were conducted to identify the influence of the amount of the slag on strain and strength properties of soil. While testing different methods were used: confined compression test, triaxial test, and direct shear. Some additional tests on prism specimen 40x40x160 mm were made in order to identify the compressive and tensile strength. Stress intensity factors were investigated as a separate set of tests.

Tests of natural clay soils and slag-soil mixture were carried out by using of above mentioned testing system IVK ASIS, which consisted of the following equipment: unconfined compression testing device, odometer, triaxial testing device, direct shear device, prism bending testing device, notched bending test device.

Usage of some devices simultaneously allows not only to reduce the testing time, but also to conduct a complex of tests simulating different stress path conditions.

Unconfined compression test. While conducting this set of tests of slag-soil mixture axial and lateral strain were measured by means of unconfined compression testing device. Methods used for soils are given in GOST 12248-2011, and methods of concrete testing are presented in GOST 24452.80.

In the Fig.3 the results of a set of unconfined compression tests of slag-clay mixture after 28 days of curing are presented.

Triaxial test. While conducting this set of tests of slag-soil mixture axial and lateral strain were measured by means of triaxial testing device. Method used for soils is given in GOST 12248-2011, and there is no standard for concrete triaxial test.

In the Fig.4 the results of slag-clay mixture tests under lateral pressure of 100 kPa with different proportion of the binder are

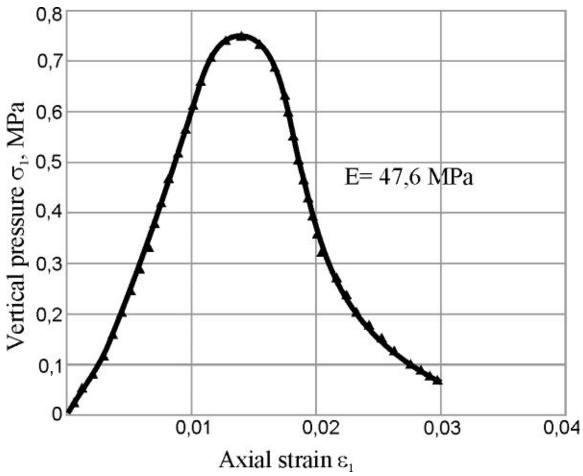


Fig. 3. Correlation between axial strain and normal pressure for the slag-clay mixture: 20 % of slag, 2 % of NaOH.

presented. As can be seen in Fig.4 with the increasing of the amount of a binder the strength of material as well as elasticity ratio increase.

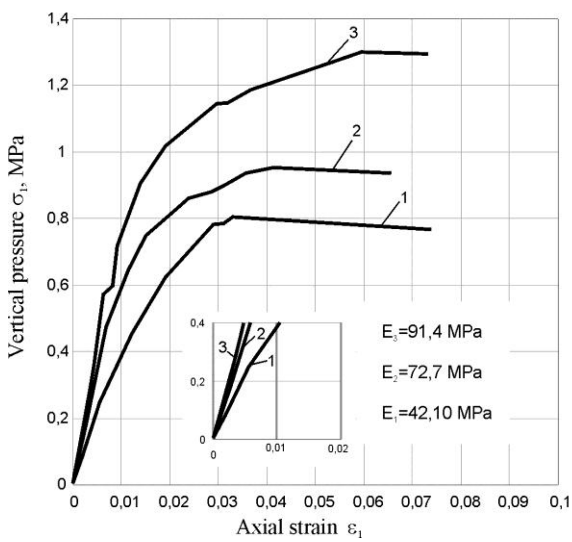


Fig. 4. Correlation between axial strain and axial pressure for slag-clay mixture:
1 – 10 % of slag, 2 % of NaOH; 2 – 20 % of slag, 2 % of NaOH; 3 – 30 % slag, 2 % of NaOH.

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